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*Author(s):* Benjamin H. Sims

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GOOD HOUSEKEEPING: SAFETY AND ORDER IN THE SCIENTIFIC LABORATORY

Benjamin Sims
Postdoctoral Researcher
Statistical Sciences Group
MS F600
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone: (505) 667-5508
Email: bsims@lanl.gov

*Safety as a form of order*

Laboratory safety might not seem, at first, to be very profoundly related to scientific knowledge. Of course safety *is* a relatively trivial issue in many scientific settings, especially in comparison to the kind of safety concerns found, say, at a construction site or a chemical plant. However, as scientific work has come to involve more exotic chemicals, biological organisms, and forms of radiation, and generally become more industrial in character, safety has become more of a concern.[1] This has occurred alongside a general expansion of government regulation of workplace safety during the 20th century, and a recent trend toward extending workplace safety efforts to new kinds of work, including administrative and professional tasks.[2] As a result of these trends, scientists find that they are increasingly being held responsible for following safety regulations in their research.[3]

In practice, safety issues in research facilities are not easily abstracted from the processes that produce scientific knowledge itself. When we use terms like "laboratory safety" we are typically referring to a set of activities or procedures designed to order the environment in such a way that danger is eliminated or contained. In the course of research, scientists are already engaged in a struggle to bring order out of chaos – to understand, predict, and modify the behavior of objects of study as well as the machines and instruments used to study them. Safety, too, depends on understanding, predicting, and modifying the behavior of research apparatus and potentially dangerous objects of study. Work safety in a particular research field is, in part, dependent on the evolving body of knowledge generated by research in that field.[4] In addition, the set of technical skills and knowledge necessary to make equipment function safely is largely the same as that required to make it produce reliable scientific results. In safety-critical scientific environments, safety efforts and research work are completely interdependent processes. Safety goals and scientific goals may be congruent, but they can just as easily demand conflicting forms of order. Safety concerns can significantly limit or alter research programs, and new research directions can generate major changes in the way safety is defined and maintained. Safety is an epistemic problem and it can have epistemic consequences.

The concept of danger is one of several that can be grouped in the overall cross-cultural category of pollution beliefs, which also includes ideas about dirt and defilement. The work of anthropologist Mary Douglas has provided a key set of analytical tools for understanding pollution beliefs and their relationship to knowledge and social structure. Douglas argues that pollution beliefs, in all their forms, emerge out of a culture's ideas about disorder. Safety, cleaning, purification, and related practices keep disorder and pollution at bay and simultaneously impose a positive, normative order on the environment.[5]

In Douglas' work, the notion of danger is particularly closely aligned with anomaly and ambiguity. People or things that don't fit into existing categories may be labeled dangerous. Situations in which social categories are uncertain – such as transitional periods between defined social states – may also be seen as dangerous. Various rituals may be employed to reinforce existing categories or to draw sharp boundaries around anomalies and ambiguities so society can be protected from them. But ambiguity is not necessarily seen as something that must simply be eliminated. It prompts efforts to impose order in part because it can also be a potent source of power. The expert authority of scientists, for example, seems to rest, in part, on the ability to order and control a potentially disorderly natural world.

Douglas' work suggests that examining pollution beliefs can bring out the connections between a society's knowledge, its moral outlook, and its social structure.[6] Along similar lines, looking at laboratory danger provides an opportunity to trace connections between scientific practice and the normative and social orders of scientific work. Historian Peter Galison, for example, cites the role of safety concerns in shaping high-energy physics research at all these levels. Galison, who also draws on Douglas, notes that physicists working at accelerator facilities fought to preserve a certain flexible, non-hierarchical "way of work life" that they considered essential to good research, in the face of efforts by the U.S. Atomic Energy Commission (AEC) to push them toward a more industrial mode of organization. Increasing concerns about accelerator safety, particularly in the wake of a deadly hydrogen-fueled fire at the Cambridge Electron Accelerator in Massachusetts, finally enabled the AEC's approach to prevail. The AEC insisted that scientists work under greater bureaucratic controls, including standard safety procedures and defined organizational hierarchies, and that they establish guidelines for access to experimental areas. It emphasized "housekeeping" as a key safety measure and requested that management enforce standards and encourage the proper 'attitude' toward housekeeping on the part of laboratory workers. Safety concerns driven by advances in accelerator technology led to a significant shift in the normative order and social organization of the high-energy physics workplace, with far-reaching consequences for the future of the field and experimental physics in general.[7]

What distinguishes safety from other ways of addressing laboratory order is the strongly normative character of safety discourse. Safety, unlike other modern ways of talking about risk, encompasses not only the possibility of harm but also the ways we expect people and machines to behave in relation to that possibility. Other ways of ordering the research environment, like those discussed above, are all normative in at least the technical sense: they specify a scientifically acceptable way of acting in relation to the objects of research. Safety can be normative in this technical sense, but it characteristically blurs the line between technical norms and broader norms of social conduct in the laboratory and its institutional context. Because of this, the study of laboratory safety is an ideal starting point for understanding the connections between the scientific approach to nature and the socially normative content of scientific work.

*Los Alamos and pulsed power culture*

This paper's argument is grounded in a nearly two-year study of safety practices at research facilities at Los Alamos National Laboratory (LANL or the Laboratory), conducted with the aim of understanding how scientists and technicians integrate safety into their work practices. This research included intensive ethnographic studies of two different areas of basic research activity at the Laboratory: bioscience and plasma physics. The bioscience study involved observation and interviews with several research teams engaged in relatively routine, low-hazard work. For the plasma physics study, I conducted interviews and engaged in participant observation as a laboratory worker in a plasma physics research facility, where the potential hazards – and corresponding safety efforts – were much more significant. The latter facility is the focus of this paper because, as a relatively high-risk environment, it provides many clear examples of the interactions between safety and the scientific research process.

Los Alamos is widely known as the place where the first nuclear weapons were developed, and the current Laboratory continues to exist primarily as a nuclear weapons research center.[8] However, the Laboratory also supports a great deal of basic research. Some of this research, such as in the biosciences, is not related to nuclear weapons at all, though it typically has some relevance to national security. Other research, in areas like plasma physics, has grown directly out of the Laboratory's weapons mission, but is oriented more toward the development and communication of scientific knowledge to a broader research community. Though they are a large portion of Laboratory employees, such basic researchers have a somewhat ambiguous place in the status hierarchy of the Laboratory: they feel they do not get quite the institutional respect accorded to researchers in the core 'weapons program', yet the open nature of their work gives them more access to professional rewards outside the Laboratory in their respective scientific fields. Focusing on these researchers gives a different perspective on the scope of scientific activities at U.S. weapons laboratories, while providing a basis for findings that may be relevant to a wider scientific community.

The plasma physics laboratory will be referred to here by the acronym CLEO.[9] It is culturally part of the scientific world of plasma physics research, but also, by virtue of its technological infrastructure, part of the "pulsed power" technical community. It is the character of this technology, more than the scientific subject matter, that structures danger in this laboratory. Pulsed power technology is characterized by the generation of very sudden and very large pulses of electrical current. One large machine at LANL is capable of producing an extremely brief current pulse of 33 MA, which is supposed to be roughly equivalent to the entire current output of every electrical generator on earth at a given moment. The CLEO apparatus is much smaller, capable of generating maximum currents on the order of 100 kA at 50kV; its capacitors can store roughly 200 kJ of electrical energy when fully charged. These pulsed have a number of scientific applications. The large electrical and magnetic fields generated can be used to energize and confine plasmas for fusion studies and to implode metal shells in weapons research; the technology can also power lasers and particle accelerators. Pulsed power research has flourished primarily at government laboratories and private R&D firms, but is currently being done in university settings as well.[10]

The most common technique for generating pulsed power in a laboratory setting is to store electrical energy in large capacitor banks – typically, arrays of capacitors called 'Marx generators'.[11] These banks are arranged in such a way that the capacitors can be charged in parallel to a certain voltage, then discharged into an electrical circuit in series, adding their voltages and generating a large pulse of current.[12] Because of the currents involved and the need to discharge the pulse almost instantaneously, pulsed power systems use an array of rather large, bizarre-looking switching devices worthy of a mad scientist's laboratory, often based on vacuum tubes and involving the deliberate production of electrical arcs. Systems have to be designed to stand up to large currents and the mechanical stresses caused by strong electromagnetic fields. Components have to be arranged to prevent arcing through the air or along surfaces between them, even though these discharges can be difficult to predict.[13] It is a further challenge to design instruments and data acquisition systems so they are adequately shielded from the electromagnetic fields generated by the pulsed power circuitry. All of these factors make designing and running pulsed power systems very specialized technical work. Becoming skilled in this area requires experience not easily acquired elsewhere, even in other types of electrical work.

Because of the high voltages, large currents, and the sheer amount of stored electrical energy involved, pulsed power work has the potential to be very dangerous. Coming into contact with the electrical equipment when it is charged could, of course, lead to a shock or electrocution; but a fully-charged capacitor bank can shock a person who comes *near* it by sending an arc through the air. When a pulsed power system is operated, an electrical fault can lead to catastrophic failures of components: capacitors can explode, cables and connectors can be blown across the room at high velocity; air arcs between components can happen with explosive intensity. If the automatic grounding system is damaged, capacitor banks can end up electrically isolated at high voltage. In such cases, a manual 'shorting stick' must be used to ground them; if done incorrectly, this can cause a sudden, explosive discharge. Even in normal operation, the high magnetic fields generated can propel loose metal objects across the lab. On top of all this, the experimental apparatus that all the electrical energy is pumped into may be designed to implode or reach very high temperatures, and laser- and x-ray-based measuring instruments can pose hazards in their own right.[14]

At Los Alamos, and probably elsewhere, pulsed power technology has evolved a distinctive work culture. This culture is built around the sense of working with something powerful and dangerous, and emphasizes the peculiar and demanding nature of pulsed power work. Safety is absolutely central to this culture. Workers, both scientists and technicians, discuss safety frequently while building and operating pulsed power systems, and emphasize their dependence on one another in safety matters. They talk about the need for 'ultimate respect for pulsed power' because it 'absolutely for a fact can kill you'[15] and how 'you don't, you know, get the opportunity to make a second mistake.'[16]

Elaborate safety arrangements and procedures are the norm, but the culture emphasizes personal responsibility for safety as well. When conflicts arise between colleagues, they are often over differing opinions on safety issues. Whether colleagues are trustworthy and competent is something people actively worry about; not surprisingly, there is some distrust of outsiders or new people in the workplace. In safety matters especially, pulsed power workers can be dismissive of colleagues, managers, or safety personnel who have demonstrated incompetence or lack of insider knowledge of pulsed power work.[17] In terms introduced by Mary Douglas and Aaron Wildavsky, they embody the characteristics of low 'grid' and high 'group': they are internally rather egalitarian, set a strong boundary between themselves and the outside world, and are intensely concerned about pollution in the form of laboratory danger.[18]

*Safety and order*

The connection between safety and the order of laboratory space emerged empirically in the way scientists, technicians, and safety personnel talked about the workplace. Specifically, discussions of safety often revolved around the issue of complexity versus messiness.[19] This was sometimes a matter of controversy within the research team, which people elaborated on in interviews. Some felt that the CLEO facility was overly messy and cluttered:

> You have, basically, three or four little experiments all shoved into the same room, which it wasn't designed for. So you've got a lot more stuff in a smaller area, so it's going to be more hazardous.[20]

Others disagreed:

> This room out here is very clean and ... compared to a lot of the experiments I've been involved with, this is a very good work space ... you know, it's clean, it's well lighted, it's not really cluttered, people take good care of their tools.[21]

Although people could have very different opinions about the current state of the facility, this seemed to be largely the result of different levels of tolerance for clutter. There was general agreement that a certain level of clutter is necessary and acceptable in a laboratory, depending on the work being done, and that beyond a certain point, clutter poses an unnecessary hazard. This general point was articulated as follows:

> The more complicated it gets ... things just have a tendency to get more and more ... maybe clutter isn't the right word, because a lot of stuff happens around the [experimental apparatus] coil ... diagnostic[s] are there, a lot of cables leading out

> from that ... even if people are as careful as they can be, there's gonna be a place where there's lots of stuff ... that doesn't mean people don't care or they're not trying real hard, that's just the way the experiment has to [be].[22]

The general concern with clutter is that it adds complexity to the laboratory environment, making it more hazardous. It can do this by directly increasing opportunities for accidents involving tripping or running into things, and also just by making it difficult to figure out what is going on with the equipment at any given moment. But not all complexity is viewed as being disorderly in a dangerous way. Instead, the emphasis is on whether the complexity makes sense – whether it is configured in a way that can be readily interpreted for scientific or safety purposes. One scientist made the distinction that 'an experiment can be crowded, but it can be logically well organized too,' offering 'evidence that somebody knew what they were doing when they put it together.'[23]:

> If I can't follow, if it's a rat's nest of piping and plumbing and wires and cables, well then I won't be able to figure out where this cable came from, and for that matter, what's on the other end of it. And then it's dangerous ... I don't have to have a tag on every single stainless steel line ... but it shouldn't be untraceable ... if twenty lines penetrate a wall and then I have to find out on the other side of the wall where they went, that starts to make it harder.[24]

The metaphor of traceability is key here. It not only points to the desire to impose some kind of rational order on the complexity of the laboratory environment, but specifically emphasizes the need for this order to be expressed visually. Pulsed power culture in general emphasizes acute visual awareness of one's surroundings as an important aspect of both technical competence and safety – probably because of the need to keep one's distance from charged equipment.[25] One technician reflected that:

> To me the good experimental operators were the ones that could see the whole aspect of the experiment from air pressures, to water temperatures, to the conditions of the banks, to whether the tools were put up or not, to whether somebody had left a door open, or forgot to hook a cable … I mean they just developed this knack for seeing problems.[26]

As described above, much has been written about how various scientific practices, inside and outside the laboratory, are meant to structure a chaotic natural world in a way that permits orderly scientific investigation.[27] The point here is that, in certain laboratory settings, man-made machinery and instrumentation can also become disorderly unless some effort is devoted to imposing structure on the laboratory environment. This structuring of the environment has epistemic consequences because it makes it possible for researchers to gain reliable knowledge about the status and functioning of laboratory equipment. This knowledge can be crucial for working safely, but the same knowledge allows scientists and technicians to make credible claims about the proper functioning of laboratory equipment. Under certain circumstances, such claims could be crucial to establishing the validity of experimental results. At the least, an untraceable problem in a technical system can hold up laboratory work because researchers want to eliminate issues that could ultimately compromise the quality of their work. In practice, as the next section shows, creating a well-structured, 'epistemically safe' work environment can be a constant struggle, in which an ideal state of order can only be approximated. This is part of the reason why neither laboratory safety nor the process of scientific investigation itself can simply be reduced to a fixed set of rules.

*Sources of uncertainty*

As we have seen, researchers have a pretty clear idea of what kind of order they want in laboratory space – visual and logical consistency, predictable connections between components, level of complexity consistent with the task at hand, cleanliness. But pulsed power systems, by their very nature, come into conflict with these ideals at nearly every turn. High performance is usually achieved at the expense of system reliability. As one scientist explained, "the voltages are too high, the spacings are too small, the currents are too high ... you just can't match your required performance and put in a lot of engineering safety factor ... the performance will degrade too much."[28] At such close tolerances, the electrical interactions between components can become very unpredictable, to the point of seeming to defy logical or scientific analysis. This uncertainty forces researchers to adopt some creative approaches to restoring order, and consequently safety, to the laboratory.

The principle source of unpredictability in pulsed power systems is the behavior of electricity itself. Because of the high voltages involved, it is relatively easy for electrical current to bypass the desired circuit and instead strike out on its own by arcing through nominally insulating materials like air. This 'breakdown' of electrical insulators is a complex and relatively poorly-understood process. The most unpredictable form of this phenomenon is 'surface-aided breakdown,' which is when an arc forms along the surface of an insulating material between electrical components. The risk of such an arc forming can be minimized by lengthening the surface path between charged components. For this reason, pulsed power machines are sometimes surreally draped and wrapped with translucent plastic: frequently, instead of separating components with a single standard insulator, researchers will separate them with layers of Mylar sheeting. This ensures that any arc will have to traverse both sides of a sheet – a distance of a couple of meters – to get from one component to the other. By using multiple layers – twenty or so – researchers ensure that an arc that might find its way through a pinpoint flaw in a single piece of plastic will have to travel around all the other layers. Despite these efforts, however, surface arcing remains extremely difficult to anticipate and control.

Arcs through open air and other insulating materials are a little easier to prevent, but are still unpredictable and can cause spectacular system failures. The arcs themselves can be explosive, generating a blinding flash and shock wave that can blow system components apart, creating shrapnel or even flying particles of molten metal. On one occasion I was shown an inch-thick steel plate from a pulsed power machine that operated submerged in oil. The arc had imprinted a fist-sized bulge on the plate – a relatively minor incident, I was told. In addition, electrical short circuits caused by arcs can send unexpected surges of current through a system. These can cause serious damage to system components; for example, the magnetic fields generated can rip metal circuit elements from their bolts. Individual components, such as capacitors, can also fail suddenly and explosively, just because they are pushed to their limits.

Arcing behavior is one of the few areas in pulsed power where system performance is seen as directly connected to standards of order in the form of cleanliness. Surface arcs can be triggered by the tiniest surface flaw or minute speck of dirt. The arc in the oil-insulted machine mentioned above was presumed to be caused by contamination that had settled out of the oil. And if small particles get stuck between layers of plastic, they can create the kind of pinpoint flaws that arcs tend to get through. Researchers try to address these problems by emphasizing cleanliness during certain stages of system assembly, such as when putting down layers of plastic sheet. But in general cleanliness is not treated as an overriding concern, because it's so hard to tell when dirt will turn out to be a problem – most of the time it doesn't seem to matter, yet sometimes arcs are attributed to tiny bits of unseen contamination. After a certain point, contamination is treated as an irreducible source of uncertainty, and systems are simply designed to be as tolerant of it as possible.

There can also be great uncertainty about the state of a system in the aftermath of an unexpected failure. A malfunction might be signaled by a flash and a bang and an automatic system shutdown, but it may not initially be obvious where the problem occurred. Careful detective work is often necessary to determine the extent of the damage. And unless and until this investigation produces a conclusive result, doubt remains about whether the capacitors in the system are still charged or not. Because failures are so common – and sometimes are not so spectacular – experienced pulsed power workers are very cautious around capacitor banks. The general practice is to act as if the banks are charged until it is proven otherwise.[29]

*Ritual and uncertainty*

In Mary Douglas' view, ideas about order are defined and enacted through ritual. The primary role of ritual is to resolve ambiguity by reinforcing categories and the boundaries between them. Rituals need not be elaborate ceremonies; they can also be relatively mundane routines that serve to structure our everyday reality. Ritual in this mundane sense, even where it is grounded in scientific principles, can still carry important symbolic meanings, according to Douglas.[30] This approach to understanding ritual has been important in the study of science and the professions because it provides a pathway toward understanding the possible connections between technical work and normative order.[31]

Pearl Katz's anthropological study of antisepsis procedures in surgery is a good example of such an analysis. She argues that 'scrubbing' procedures, draping of patients, and the elaborate rules about how to move and what can be touched serve not only to make things sterile, but also to establish clear symbolic boundaries between sterile and non-sterile. By reducing ambiguity in the environment, these boundaries enable doctors and nurses to move more freely and work more efficiently.[32] Others have gone further with this type of analysis. Stefan Hirschauer argues that antisepsis and other pre-surgical procedures serve to distance physicians from the everyday world and from their patients as persons, so that they may cut into patient's bodies without the feelings of shame or guilt this might otherwise cause.[33] For my present purposes I focus, as Katz does, primarily on how rituals structure the environment in ways that enable the exercise of technical expertise, although in the end the rituals in question also appear to carry abstract symbolic significance of the sort that Hirschauer examines.

Ambiguity about system status appears to be the most worrisome source of danger for scientists and technicians at CLEO. At a basic level, charged high-voltage equipment itself is a potential source of danger even when it is working just as expected. Under such ideal conditions, danger would be relatively predictable and could be mitigated simply by keeping one's distance from certain charged parts. But anomalies in system performance are endemic to pulsed power work. The more worrisome source of danger is that it is frequently difficult to obtain certain knowledge about where hazards lie. Under these conditions, even someone with appropriate technical training might be misled into putting themselves in danger. Experienced pulsed power workers tend to be acutely aware of how uncertain their knowledge about these systems can be.

One way to maintain order in the face of ambiguity is to eliminate the ambiguity. Another way is to contain the ambiguity in such a way that it cannot threaten order. Both strategies are used at different times in pulsed power work. In facilities like CLEO, equipment is actually only charged for a brief period of time before each experimental run, or 'shot.'[34] Most of the time, equipment is grounded and power is turned off, and people work freely throughout the laboratory space. In this state, uncertainty about system safety is systematically eliminated by 'locking out' high-voltage power sources and by several redundant grounding mechanisms that ensure, and visually demonstrate, that equipment cannot be electrically charged. In the charged state, by contrast, uncertainty about system behavior is treated as an unavoidable problem – a necessary trade-off for high performance. To keep this uncertainty from threatening the safety of the laboratory, the charged system is enclosed by clear boundary in the form of a 12-foot-tall metal and plywood 'blast wall' that surrounds the entire pulsed power system, preventing human access and containing any flying debris. This wall eliminates the need for certain knowledge about hazards by enclosing the entire area of ambiguity.[35]

Each of these two states represents an acceptable form of order in pulsed power culture. But as Douglas points out, the most significant danger is often located in the transitions between states of order, and ritual tends to play an especially strong role in managing such transitions.[36] In fact, it is in the transitions between charged and uncharged that safety takes its most ritualistic and procedural turn in the pulsed power laboratory.

A pre-shot procedure is followed to prepare for the transition from an uncharged to a charged state. Before the doors are closed in preparation for a shot, rotating emergency lights are turned on. A designated system operator then searches the experimental area for people. This person has to press 'sweep buttons' in several locations to verify that they have checked the area and it is unoccupied. The sweep buttons must be pressed and the door closed within a specified time period or the whole procedure must be started again. Immediately before a shot, warning horns sound to alert anyone missed in the sweep, and announcements that charging will commence are broadcast over the public address system. If someone were to be trapped in the danger zone, they could press one of a number of 'scram' buttons that immediately terminate the experiment and ground the equipment.[37] Experimental operations are carried out remotely from a control room outside the blast wall.

Following a shot, equipment is treated as potentially charged until proven otherwise. The transition to a verified uncharged state is managed through a set of procedures known as 'safing.' This term represents a complete verb form of the word 'safe' – one can 'safe' a system or verify that it has been 'safed,' for example. Safing involves turning off all high-voltage power supplies and positively connecting all system components to ground. Pulsed power systems usually have mechanized safing systems that do this automatically, but manual procedures are still followed, partly as a check on the automatic system. The basic tools of the manual safing process are called 'shorting sticks.' These are brightly colored wood or fiber glass poles, about size of a broom handle, with a metal hook on the end that is connected via a cable, through a resistor, to ground. Each major piece of equipment has its own dedicated shorting hook. The resistor – often a large tub of water – provides a 'soft short' that enables equipment to discharge relatively slowly, minimizing the risk of arcing between the hook and any charged equipment.

At CLEO, the manual safing procedure can only be carried out by scientists and technicians who have been trained as 'safing operators.' Two safing operators open the blast wall door and enter the experimental enclosure. One performs the procedure and the other serves as a safety watch and backup. They proceed to hook the shorting sticks onto their corresponding pieces of equipment, following a predetermined sequence that keeps the team away from potentially charged equipment until they have succeeded in manually grounding it. Once this process is complete, others are allowed free access to the experimental area again.

One of the explicit functions of safing is to structure the laboratory environment so that scientists and technicians can visually verify the grounded status of every piece of equipment. The brightly-colored shorting sticks are designed to be noticeable, so that a stick out of place would immediately stand out to those familiar with the laboratory. Safing systems also extend the theme of traceability. The cables that connect the shorting sticks to ground, for example, are deliberately purchased with transparent plastic insulating material, just so the integrity of the metal part of the cable can be easily verified.[38] System designers try to have the sticks connect as directly as possible to possible reservoirs of electrical charge, so the connections will be more robust and more easily traceable:

> the philosophy is to make sure that your manual system will fully dissipate a fully-charged system safely, regardless of what connections may or may not have

> been blown off. And so ... you want to have your manual system address the capacitors as directly as possible. You don't want to be shorting them out over here assuming some connections are in place.[39]

This philosophy came into play during the design of the CLEO safing system when a dispute broke out among the researchers about whether a particular capacitor bank required one or two shorting hooks. One technician argued that the circuit would always keep the two main parts of the bank's chassis at the same electrical potential, so only one hook was required. However, the bank ultimately got two hooks, because the majority of scientists and technicians were worried about the lack of a verifiable electrical connection between the two parts – the fact that "you could not actually see a physical connection."[40]

Safing procedures are rituals to make the laboratory a comfortable and secure work space according to the standards of order of the pulsed power community. This community defines order, and safety, primarily in terms of the traceability of connections between system elements. The manual safing procedure produces this type of visual environment by creating an easily readable configuration of brightly-colored shorting sticks that are connected to ground by visually verifiable connections.

The ritual aspects of safing procedures are underscored by the community's reluctance to rely solely on automatic safing systems. Though these systems are by all accounts very effective, they are not fully trusted to create a safe environment. This is partly related to the general reluctance to assume that any aspect of a pulsed power system can be counted on to behave predictably. More importantly, automatic systems fail to provide appropriate visual cues: they may render the system safe in technical terms, but they don't order the environment in a meaningful way – one that enables individual workers to directly and continuously verify the safety of the system.

Safing also plays an important role in defining the relationship between people and equipment in the laboratory. Discussions on how to design a safing system, like the one described above, are carried out with great seriousness by the participants, with a heavy emphasis on technical knowledge and past experience. This conveys to everyone – including new members of the community – that safety procedures are an important and integral part of technical work in this setting. This message is also conveyed in the evident care with which the safing procedure itself is carried out. Watching the procedure enacted is like watching a morality play in which the actors, through gesture and attitude, very literally demonstrate the concept of 'ultimate respect' toward pulsed power equipment.

The pre-shot safety procedure is not quite as symbolically loaded in this respect because it does not involve the same sort of direct confrontation between people and potentially charged electrical equipment. Because it definitively cuts off human access to an area of potential danger before the danger is actually present, it does not require the careful balancing of risk against order that is characteristic of safing. Still, it helps define the relationship between workers and pulsed power equipment by clearly drawing spatial and temporal boundaries around a set of circumstances in which any direct interaction between the two must be strictly forbidden.

Safety procedures also seem to play a key role in defining the relationships between people in the pulsed power community. It has been observed in many other laboratory settings that the scientific community seems to place a greater value on purely intellectual work than on work involving manual skill. This valuation of "head" over "hand" is reflected in various status hierarchies, such as the greater esteem generally granted to theoreticians over experimentalists, or the supervisory control scientists have over the work of laboratory technicians.[41] These distinctions clearly apply in pulsed power as well: it is the scientists who go to conferences, publish papers, and generally reap the rewards of laboratory work; they also direct the work of technicians and decide which technicians they want to work in their facility.

In the CLEO lab, however, safety concerns seem to provide a basis for an alternate hierarchy in which hands-on working experience and skill are the primary determinants of social status. This alternate hierarchy appears particularly strongly during a shot, and through the pre- and post-shot safety procedures. At these times, the movements of less-experienced and less-skilled members of the team are essentially controlled by those with operating experience, who carry out the procedures and ensure they are completed satisfactorily. The experienced group is made up largely of technicians, but includes some scientists as well; they other group is a mix of students, younger technicians, and less-skilled scientists. Even one of the principle investigators fell into this latter category at the time of this study, though he was in the process of being trained to be a system operator.

This skill-based hierarchy carries over into everyday lab work as well. Scientists seemed to defer to technicians, or at least treat them as equals, in many decisions involving safety or system configuration. Scientists even judged each other according to their skill and ability to work safely. For example, one scientist explained that he had little tolerance for 'klutzes,' colleagues who repeatedly make mistakes in the laboratory:

> I mean there are, there are staff [scientists] who we don't want in our labs, 'cause they just are klutzes, and they're known to be klutzes … even some staff that are supposed to be experimentalists … it's really hard to undo that reputation … there's guys I know who are marked as klutzes forever, and … rightfully so.[42]

This emphasis on skill and intolerance of incompetence was a repeated element of conversation among all members of the CLEO team, who had some internal disagreements about which team members they considered more or less skilled or safety-conscious. Their harshest criticisms, however, were directed at outsiders who were not familiar with pulsed power work yet presumed to get involved in laboratory safety. Safety personnel bore the brunt of this antagonism, but it was also directed at many managers and even colleagues. Safety, and the related emphasis on skill and experience of colleagues, seemed to be one basis for drawing firm social boundaries between the

CLEO team and the outside world and for maintaining a sense of solidarity among team members.

In summary, the pulsed power community demonstrates an overriding commitment to safety occasioned by a firm belief in the dangers inherent in the electrical currents used. This commitment to safety is enacted and reinforced in the community through the use of safety procedures that also serve ritual functions. These procedures help define the norms for interactions between people and laboratory equipment, and between people. They help create a close-knit social group that is also rather suspicious of outsiders, and which relies on skill and experience, as much as scientific authority, as determinants of social status. The causal relationships are complex, however; it may be that the close, egalitarian social organization of the group, which is related to the style of work in pulsed power, is what makes it possible to pay such close attention to safety in the first place.

*Safety in the Biosciences*

While the pulsed power lab provides fertile ground for examining the relationships between safety and order in scientific work, it is an individual facility with a very distinct local culture. A brief overview of the bioscience research culture at LANL provides some useful contrasts. Despite the common institutional background, the relationship between safety and order is defined very differently in the biosciences. LANL bioscience facilities don't deal with infectious organisms, so the work is understood to be relatively low-risk. The greatest dangers come from cumulative exposure to toxic or cancer-causing chemicals, but both the possible contamination and its consequences are largely invisible. Not surprisingly, bioscience researchers place little stock in visual evaluation of the work space, and are not very concerned about maintaining visual consistency or logical traceability in the laboratory environment. Instead, they protect against contamination by wearing gloves and other protective equipment, and by cleaning up spills of powders or liquids.

Safety procedures in the biosciences are relatively simple and are taken care of largely at the individual level. This is consistent with the way bioscience research work is organized. In the pulsed power laboratory, a regular cast of characters reports to the same location every day, where they work together on a large, fixed technical system. In the biosciences, teamwork usually involves coordinating multiple individual work trajectories rather than working together in a shared space. Compared to the CLEO team, bioscience research teams are more hierarchical and less integrated internally, and boundaries with outside groups seem correspondingly less important. Bioscience safety procedures don't appear to carry the ritual weight needed to generate strong community solidarity and sharp boundaries with the outside world in this diffuse social context.[43]

*Conclusion*

As the bioscience study demonstrates, safety is not always a major determinant of how scientific work will be structured. The contrast between pulsed power research and bioscience research does, however, suggest certain regularities in the relationship between safety and work that are similar to those found by Douglas and Wildavsky. Greater concern with safety seems to go along with a close-knit social group that is internally rather egalitarian and draws a sharp boundary between itself and the outside world. This relationship itself may not show up this clearly in all cases, however. But this study demonstrates that safety can be a central aspect of laboratory culture, and one which implicates many other important cultural themes, including the role of order in the scientific research process, the norms that shape interactions in the laboratory, the status structure of the scientific workplace, and the interface between scientists, institutions, and the public.[44] Safety is one of those middle-level concepts, like trust or skepticism, that can help us talk about the moral order and social structure of science without abandoning a commitment to examine scientific practice. The feature that distinguishes safety from these other concepts is that it is embedded in institutional arrangements peculiar to the last 60 years or so, so it has the potential to tell us much about the changing nature of scientific work, the role of organizational context in scientific work, and broader issues about public trust in science.

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[1] See, for example, the account of the influence of safety concerns on the development of high-energy physics in Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997), 352-62.

[2] On the early history of the U.S. work safety movement, see Mark Aldrich, *Safety First: Technology, Labor, and Business in the Building of American Work Safety, 1870-1939* (Baltimore: Johns Hopkins University Press, 1997). U.S. government regulation of workplace safety expanded significantly with the passage of the Occupational Safety and Health Act (OSHA) in 1970; see Benjamin W. Mintz, *OSHA: History, Law and Policy* (Washington, D.C.: Bureau of National Affairs, 1984). The expansion of safety efforts to different types of work probably has its origins in the movement in the corporate world toward 'continuous improvement' in business processes. Recent approaches to industrial safety have emphasized the modification of individual behavior and organizational culture, rather than the work environment, as holding the greatest potential for further improvement in safety. They have also suggested that significant safety improvements can be made even in low-risk work environments. On 'behavioral safety,' see Thomas R. Krause, John H. Hidley, and Stanley J. Hodson, *The Behavior-Based Safety Process: Managing Involvement for an Injury-Free Culture* (New York: Van Nostrand Reinhold, 1990) and E. Scott Geller, *Working Safe: How To Help People Actively Care for Health and Safety* (Boca Raton: CRC Press, 1998). On 'safety culture,' see International Nuclear Safety Advisory Group, *Safety Culture*, vol. No. 75-INSAG-4, *Safety Series* (Vienna: International Atomic Energy Agency, 1991); Dominic Cooper, *Improving Safety Culture: A Practical Guide* (Chichester, UK: John Wiley and Sons, 1998); and A.I. Glendon and N.A. Stanton, 'Perspectives on Safety Culture', *Safety Science*, Vol. 34 (February-April 2000), 193-214.

[3] Scientists in industry have worked under this assumption for decades, while government laboratories have placed increasing emphasis on workplace safety over the last ten years or so. By comparison, many laboratories at academic institutions still seem to face relatively little pressure to conform to safety rules, though this could be changing. For a discussion of the enforcement of safety regulations in an academic setting, see pages 21-23 in Cyrus C.M. Mody, 'A Little Dirt Never Hurt Anyone: Knowledge-Making and Contamination in Materials Science', *Social Studies of Science,* Vol. 31 (February 2001), 7-36.

[4] As Stephen Hilgartner argues in relation to the social problems literature, 'we cannot assume that the process of linking an object to a putative harm is independent of the process that defines the object as an *object.*' Quote at p. 41 in Stephen Hilgartner, 'The Social Construction of Risk Objects: Or, How to Pry

Open Networks of Risk', in James F. Short, Jr. and Lee Clarke (eds), *Organizations, Uncertainties, and Risk* (Boulder, CO: Westview Press, 1992), 39-53.
[5] CITE DOUGLAS.
[6] also others who have followed: Specifically Galison, Mody, Traweek, etc. or perhaps a separate note on anthropological sources including Laura, Sheila Zabusky, etc. Things to cite about Traweek: General concern with symbolic aspects of things; p. 39-40 discussion of "radiation fence," things that can't be easily classified/bounded as dangerous, forbidden=sacred, "it is a symbol of the lab's restraint, its responsibility in its dealings with the community; it is also a symbol of the lab's very great and dangerous power." (40) Also CITE more recent work on moral context of science: Owen-Smith, Vaughan, Mody. On the moral economy of science see, for example, Lorraine Daston, 'The Moral Economy of Science', *Osiris,* Vol. 10 (1995), 3-24; Peter Dear, 'From Truth to Disinterestedness in the Seventeenth Century', *Social Studies of Science,* Vol. 22 (1992), 619-31; Theodore M. Porter, *Trust in Numbers: The Pursuit of Objectivity in Science and Public Life* (Princeton: Princeton University Press, 1995); Charles Thorpe and Steven Shapin, 'Who Was J. Robert Oppenheimer? Charisma and Complex Organization', *Social Studies of Science,* Vol. 30 (August 2000), 545-90. On the origins of the laboratory specifically, see Steven Shapin, *A Social History of Truth: Civility and Science in Seventeenth-Century England* (Chicago: University of Chicago Press, 1994); Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton: Princeton University Press, 1985).
[7] CITE GALISON
[8] A few excellent ethnographic studies have been done on weapons-related work at U.S. National Laboratories. The most well-know of these is Hugh Gusterson's study of Lawrence Livermore National Laboratory scientists, Hugh Gusterson, *Nuclear Rites: A Weapons Laboratory at the End of the Cold War* (Berkeley: University of California Press, 1996). On Los Alamos specifically, see Andrew C. Koehler, 'Design for a Hostile Environment: Technical Policymaking and System Creation' (Doctoral Thesis, University of California, Berkeley, 2001) and Laura A. McNamara, 'Ways of Knowing About Weapons: The Cold War's End at the Los Alamos National Laboratory' (Doctoral Thesis, University of New Mexico, 2001).
[9] I use an invented acronym (a pseudoacronym?) here to preserve the anonymity of my subjects, and to reflect the fact that the names of many pulsed power facilities and experiments are acronyms.
[10] For an overview of current problems in pulsed power, the wide variety of its applications, and where research is being done, see the recent special pulsed power issue of *IEEE Transactions on Plasma Science,* Vol. 28, No. 5 (October 2000).
[11] Marx's contributions to the understanding of power are well known. Marx banks are named after their inventor, Erwin Marx. (REFERENCE?) Another particularly entertaining method of generating pulses of power is to use high explosives to drive a magnetized metal core through a wire coil. (REFERENCE)
[12] E. Kuffel and W.S. Zaengl, *High-Voltage Engineering: Fundamentals* (Oxford: Pergamon Press, 1984), 65-72.
[13] The TEA lasers described in H.M. Collins, 'The TEA Set: Tacit Knowledge and Scientific Networks', *Science Studies,* Vol. 4 (1974), 165-86 and H.M. Collins, *Changing Order: Replication and Induction in Scientific Practice* (Chicago: University of Chicago Press, 1992), 51-78 are smaller pulsed power devices, and this precise problem is central to Collins' discussion of replication. In both cases, the goal is to arrange electrical components to discharge power in a controlled manner without unwanted arcing between components, and the primary challenge is to anticipate the complex and unpredictable behavior of these electrical discharges.
[14] For an overview of electrical hazards relevant to pulsed-power work, see Lloyd B. Gordon, 'Electrical Hazards in the High Energy Laboratory', *IEEE Transactions on Education,* Vol. 34 (August 1991), especially 231-236.
[15] Interview, Physics Division Scientist #2, June 5, 2001.
[16] Interview, Physics Division Scientist #3, June 7, 2001.
[17] The social science literature on technicians touches on similar issues of identity, boundaries, and technical expertise. On laboratory technicians, see Stephen Barley and Beth Bechky, 'In the Backrooms of Science: The Work of Technicians in Science Labs', *Work and Occupations,* Vol. 21 (1994), 85-126; Chandra Mukerji, *A Fragile Power: Scientists and the State* (Princeton: Princeton University Press, 1989),

125-45; Steven Shapin, 'The Invisible Technician', *American Scientist,* Vol. 77 (1989), 554-63; Shapin, *A Social History of Truth: Civility and Science in Seventeenth-Century England*, 355-407; Benjamin Sims, 'Concrete Practices: Testing in an Earthquake-Engineering Laboratory', *Social Studies of Science,* Vol. 29 (1999), 483-518. On technicians more generally, see Stephen Barley, 'Technicians in the Workplace: Ethnographic Evidence for Bringing Work into Organization Studies', *Administrative Science Quarterly,* Vol. 41 (1996), 404-40; Christopher Henke, 'The Mechanics of Workplace Order: Toward a Sociology of Repair', *Berkeley Journal of Sociology,* Vol. 44 (2000); Julian Orr, *Talking About Machines: An Ethnography of a Modern Job* (Ithaca, NY: Cornell University Press, 1996); and the essays in Stephen R. Barley and Julian E. Orr (eds.), *Between Craft and Science: Technical Work in U.S. Settings* (Ithaca and London: Cornell University Press, 1997), especially Bonalyn J. Nelsen, 'Work as a Moral Act: How Emergency Medical Technicians Understand Their Work', in Stephen R. Barley and Julian E. Orr (eds), *Between Craft and Science: Technical Work in U.S. Settings* (Ithaca and London: Cornell University Press, 1997) and Stacia E. Zabusky, 'Computers, Clients, and Expertise: Negotiating Technical Identities in a Nontechnical World', in Stephen R. Barley and Julian E. Orr (eds), *Between Craft and Science: Technical Work in U.S. Settings* (Ithaca and London: Cornell University Press, 1997).

[18] Mary Douglas and Aaron Wildavsky, *Risk and Culture: An Essay on the Selection of Technical and Environmental Dangers* (Berkeley: University of California Press, 1982) (NEED PAGE REF)

[19] The connection between safety and housekeeping is commonly mentioned in industrial safety textbooks. See, for example, Willie Hammer, *Occupational Safety Management and Engineering*, 4th ed. (Englewood Cliffs, NJ: Prentice Hall, 1989), 188 and David L. Goetsch, *Occupational Safety and Health for Technologists, Engineers and Managers*, 3rd ed. (Upper Saddle River, NJ: Prentice Hall, 1999), 332. On the use of housekeeping as an indicator of safety in companies, see Cooper, *Improving Safety Culture: A Practical Guide*, 246-47; in high-energy physics laboratories, see Galison, *Image and Logic: A Material Culture of Microphysics*, 360.

[20] Interview, Physics Division Technician #2, June 5, 2001

[21] Interview, Physics Division Technician #1, March 2001

[22] Interview, Physics Division Technician #1, March 2001.

[23] Interview, Physics Division Scientist #2, June 5, 2001.

[24] Interview, Physics Division Scientist #2, June 5, 2001.

[25] Emphasizing the importance of the visual, one scientist told me a story about researchers at a laboratory in California who were working with a fully-charged pulsed power system when an earthquake hit, shutting off all power and lighting in their windowless facility (the capacitor banks, of course, remained charged) and their fear as they groped through the darkness trying to find a way out!

[26] Interview, Physics Division Technician #1, March 2001.

[27] On the transformation of the natural world through laboratory work, see Bruno Latour and Steve Woolgar, *Laboratory Life: The Construction of Scientific Facts* (Princeton: Princeton University Press, 1986); Michael Lynch, *Art and Artifact in Laboratory Science: A Study of Shop Work and Shop Talk in a Research Laboratory* (London: Routledge and Kegan Paul, 1985); Karin Knorr-Cetina, *The Manufacture of Knowledge: An Essay on the Constructivist and Contextual Nature of Science* (Oxford: Pergamon Press, 1981); Mody, 'A Little Dirt Never Hurt Anyone: Knowledge-Making and Contamination in Materials Science', (. On the use of environmental features to structure human cognition more generally, see Jean Lave, *Cognition in Practice: Mind, Mathematics and Culture in Everyday Life* (Cambridge, UK: Cambridge University Press, 1988) and Edwin Hutchins, *Cognition in the Wild* (Cambridge, MA: MIT Press, 1995). For a discussion specifically on the structuring of various environments to enable the application of visual expertise, see Charles Goodwin, 'Professional Vision', *American Anthropologist,* Vol. 96 (1994), 606-33.

[28] Interview, Physics Division Scientist #3, June 7, 2001.

[29] INTERVIEW CITATION ON THIS?

[30] Mary Douglas, *Purity and Danger: An Analysis of Concepts of Pollution and Taboo* (London: Routledge & Kegan Paul, 1966), 69.

[31] CITATIONS?

[32] Pearl Katz, 'Ritual in the Operating Room', *Ethnology,* Vol. 20 (1981), 335-50.

[33] Stefan Hirschauer, 'The Manufacture of Bodies in Surgery', *Social Studies of Science,* Vol. 21 (1991), 279-319. Hirschauer's paper triggered a debate on whether social explanations of technical practices should stick closely to the 'form of life' of the research subjects – in this case, surgeons – or whether more abstract analyses of the symbolism in technical practices can be useful. See H.M. Collins, 'Dissecting Surgery: Forms of Life Depersonalized', *Social Studies of Science,* Vol. 24 (1994), 311-33; Stefan Hirschauer, 'Towards a Methodology of Investigations into the Strangeness of One's Own Culture: A Response to Collins', *Social Studies of Science,* Vol. 24 (1994), 335-46; Nicholas Fox, 'Fabricating Surgery: A Response to Collins', *Social Studies of Science,* Vol. 24 (1994), 347-54; Michael Lynch, 'Collins, Hirschauer and Winch: Ethnography, Exoticism, Surgery, Antisepsis, and Dehorsification', *Social Studies of Science,* Vol. 24 (1994), 354-69; and, finally, H.M. Collins, 'Scene from Afar', *Social Studies of Science,* Vol. 24 (1994), 369-89. I believe either style of explanation can be valuable, depending on what claims one wants to make, and that the sociology of science should make room for more of the latter type of analysis.

[34] This term was probably adopted from the same term used for nuclear tests and high-explosive experiments at the Laboratory; the connection may have arisen through early experimentation with explosives-driven induction pulsed power devices.

[35] SOURCE FOR THIS? HCP?

[36] CITE DOUGLAS

[37] A term adopted from similar buttons for rapid shutdown of nuclear reactors.

[38] SOURCE?

[39] Interview, Physics Division Scientist #3, DATE?

[40] Interview, Physics Division Technician #1, DATE?

[41] NEED REFERENCES ON THIS

[42] Interview, Physics Division Scientist #2, DATE?

[43] For example, there appear to be much sharper, more traditional status distinctions between scientists and technicians in the biosciences. Perhaps not coincidentally, the majority of bioscience technicians are female, while pulsed power technicians are overwhelmingly male.

[44] Researchers' moral universe extends into the technical details of their work; or, their scientific and technical views of order spill over into the social organization of the laboratory. The concept of laboratory safety, with its mixture of technical and social prescriptions for order, helps us understand this continuity.